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955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Effects of SOH Sizing on Payload/Gross Weight, and Performance Sensitivity to Core Inert Weights

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AUTHOR(S)- D. E. Cassidy
J. J. Schoch

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ABSTRACT

The stage and one-half to orbit integral launch system can be substantially more efficient if sized to deliver relatively large payloads due to a large non-linear effect from the fixed weights in the core vehicle.

Based on an approximate weight scaling relationship, and an assumption of 20,000 lbs core fixed weight, an increase in payload capability from 10,000 lbs to 50,000 lbs would require an increase in gross launch weight from 700,000 lbs to 1.43 million pounds.

For a fixed gross launch weight, a 16% increase in the core vehicle inert weight (with fixed core propellant weight) would completely eliminate the payload capability of a 10,000 lb payload system; however, there would still be 69% of the payload capability (34,500 lbs) remaining in a 50,000 lb payload system.

In the case where the drop tanks are allowed to increase in size in order to keep a fixed payload (again for fixed core propellant), a 16% increase in the core inert weight would require about 18% increase in the drop tank weight for the 10,000 lb payload system, and a 14% increase in drop tank weight for the 50,000 lb payload system.

The commonly used inert stage fraction (λ) can be very misleading in relating the SOH performance sensitivity to variations in the core inert weight. In the case of fixed core propellant, a percent variation in core λ corresponds to a 2 to 3 times greater percentage variation in core inert weight.

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SUBJECT: Effects of SOH Sizing on Payload/Gross Weight, and Performance Sensitivity to Core Inert Weights

DATE: March 13, 1969

FROM: D. E. Cassidy
J. J. Schoch

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TECHNICAL MEMORANDUM

I. Introduction

The stage and one-half integral launch and reentry vehicle (SOH) represents a development and performance compromise between a highly sensitive fully reusable single stage to orbit launch vehicle (SSTO) and a less sensitive two stage to orbit vehicle which has a reusable upper stage and might or might not have a reusable lower stage. The SOH concept is illustrated in Figure 1a. The SOH expendable strap-on tanks are staged during ascent and not integrated into the reusable spacecraft (SOH core), as would be the case for a SSTO type vehicle. The SOH system, therefore, has the performance advantage of some staging as well as eliminating added inert weights that would be required if the tanks were recovered. On the other hand, the full advantage of staging is not achieved since only the propellant tanks are dropped during the ascent, and the high thrust engines and associated structure are carried into orbit. For this reason the SOH lies somewhere between a reusable SSTO and a two stage system in payload performance and sensitivity.

Depending on the payload weight, the SOH system payload can be very sensitive to core vehicle inert weight variations. Both the gross weight to payload weight (growth factor) and the sensitivity of growth factor to the core vehicle inert weight increase quite rapidly at payloads less than about 20,000 pounds or so. This is also the payload range in which SOH design concepts generally have been studied to date. On the other hand, the results of this study show that for larger payloads of about 40,000 to 50,000 pounds, the SOH payload can be made considerably less sensitive to the core inert weights resulting in a more attractive launch system.

The large payload sensitivity of the SOH, at low payload weights, results from the inert weights of the core sub-systems, structure and minimum propellant tankage which can be thought of as essentially fixed and independent of the payload. That is, it takes some minimum weight to conduct the mission and support the crew even without payload. Some idea of the approximate magnitude of these fixed weights is presented in Figure 2. The fixed weights can be quite large and range somewhere in the neighborhood of 18,000 to 25,000 pounds for the SOH type spacecraft.

The effects of the fixed weights on the SOH system are investigated in the sections that follow. The SOH performance data was generated with a trajectory program which computes optimum ascent trajectories. An approximate weight scaling relationship between the major systems weights is then applied to compute payload, determine the growth factors, growth factor sensitivity and the variations with payload and gross weight.

II. Payload Weight Scaling Model

The model used for scaling the SOH core vehicle weight is based on the sketch in Figure 1b. Although this model is only an approximation, it contains the essential features which reflect the effects of scaling. As the payload capability is increased, the propellant tankage and engine system increase. The fixed weights are then combined with the tankage and engine weights, and the additional weight factors are added to account for the shell structure and reentry heat protection system, recovery and landing system, and the orbital maneuvering propulsion system (including propellant). The method is outlined in Figure 3 along with the final weight scaling equation (iii).

In equation (iii), the payload is expressed as a function of WIEO, WPC, WFIX, WE and a structural factor (KPL) to account for carrying payload. For the purposes of this study, however, the discretionary payload weight does not account for KPL so that the payloads presented in the figures that follow include the structure associated with supporting the payload. In order to estimate this structural factor it is necessary to decide on how the payload should be carried. For the large payload weights and sizes it might be more desirable to have the capability of carrying payload external to the core vehicle. Just how the large payloads might effect the SOH configuration and performance was not investigated in this study.

III. SOH Performance

Weight in Earth Orbit

The gross weight placed in earth orbit (WIEO) for a stage and one-half type system employing an estimated high performance (high pressure, two position nozzle) LH_2-LO_2 engine system is presented in Figure 4 as a function of drop tank propellant weight. Launch thrust to weight ratio was assumed to be 1.25, maximum throttling during ascent 10 to 1, and maximum allowable acceleration 5G. The ascent trajectory follows a gravity turn prior to drop-tank staging, followed by a linear tangent flight path after staging to an 100 nm circular orbit (72° lauch azimuth). The WIEO is then maximized by optimizing on the initial kick angle and the time at which the engine is throttled back to minimum thrust.

The drop tank propellant weights and the WIEO are normalized to launch gross weight. The two curves show the effect of the drop-tank inert fraction (λ_1 defined in Figure 4). Since the present concept of the expendable drop tanks consists of a simplified aluminum structure coated with external insulation, the inert fraction can be quite low. Current estimates place it about 5%. This value will be considered reasonable for the purposes of this study.

The curves on Figure 4 also illustrate that the WIEO decreases as the drop tank size increases in relation to the gross weight, i.e., as more of the total ΔV is put into the drop tanks and less into the core vehicle. However, the WIEO in addition to the payload weight also contains the core vehicle inert weights including the fixed weights, core propellant tankage, maneuvering and deorbit propulsion, residuals, engine system, structure and reentry heat protection, and the recovery systems. The amount of the WIEO actually available for payload depends on the core inert weights. The scaling equation (iii) was used to convert from the WIEO to payload weight.

Optimum Staging for Maximum Payload

The payload derived from equation (iii) for a one million pound gross launch weight system is presented in Figure 5 as a function of core fixed weight and the ratio of core propellant to total propellant weight. Also included in Figure 5 are the corresponding core vehicle inert fractions (λ_{IC} defined in Figure 5) and staging velocities (vehicle inertial velocity).

The maximum payload in Figure 5 is achieved when about 10% of the ascent propellant is in the core vehicle. The point where the optimum occurs is insensitive to the magnitude of fixed weights, and for a given fixed weight the payload reduces gradually for off optimum staging. This latter effect could provide some flexibility in choosing the core propellant size.

The curves of constant core vehicle inert fraction, on the other hand, indicate that for a constant value of λ_{IC} in the range of interest, the maximum payload would be achieved when all of the ascent propellant is in the drop tanks and that the payload is very sensitive to the staging conditions. However, it is not possible to follow a constant λ_{IC} curve in a real case due to the large fixed weights in the core. Therefore, the λ_{IC} cannot be used as a performance sensitivity parameter by itself and, in fact, can be quite misleading.

Figure 5 shows that when the more realistic scaling equation (iii) is employed, the SOH system is relatively insensitive to off optimum staging. This provides some flexibility in sizing the core vehicle propellant capacity and, as will be discussed later, permits drop-tank growth to compensate for core vehicle inert weight growth with only a relatively small penalty from off-optimum staging.

IV. Size Effect on System Efficiency

The ratio of gross launch weight to payload weight (growth factor) is presented in Figure 6 as a function of gross weight, for the near optimum 10% core propellant ratio derived from Figure 5. Although a constant value of λ_{IC} would give the same growth factor for any gross weight and, therefore, no improved efficiency with size, a more realistic scaling equation shows dramatic effects. At the low gross weight end of the curves the SOH system can inject only the core vehicle into orbit resulting in the high growth factor. For the large gross weights, on the other hand, the effect of the fixed weights are small compared to the payload, and the actual core inert fraction is reduced. If 20,000 pounds is assumed for the core fixed weights, as an example, the payload can be increased from 10,000 to 50,000 pounds (a factor of 5) while the gross weight increases from 700,000 to 1.43 million pounds (a factor of 2)*. This reduction in growth factor is quite strong for fixed weights of any reasonable size.

*These magnitudes are approximations based on the weight scaling equation. The trends and potential weight differences are the major points of the scaling effect.

The effect of size can also substantially reduce the sensitivity of the payload and gross weight to increases in the core inert weight. In the following section, the sensitivity of the SOH system to core inert weight growth will be investigated for cases where the core propellant weight is fixed and the core inert weight increases. This could well be the case during a vehicle hardware development program where the vehicle design is essentially fixed except for the inevitable inert weight growth.

V. Performance Sensitivity to Core Inert Weight Growth

As pointed out previously, λ_{IC} is not an accurate sensitivity parameter for determining the effects of changes in core inert weight on the SOH system performance. The plot on Figure 7 illustrates this point for the case of fixed core propellant. Although variations in λ_{IC} are approximately equal to variations in WIC at the values of inert fractions characteristic of conventional expendable stages, variations in λ_{IC} correspond to 2 or 3 times the variation in WIC in the case of the SOH core vehicle. This means that a 10% increase in λ_{IC} is equivalent to a 20 to 30% increase in the core inert weight. For this reason the inert weights are used directly to determine the SOH performance sensitivities. With a fixed core vehicle propellant, then, what is the sensitivity of:

a) The payload weight to increases in core inert weight for a fixed gross weight, and

b) The required drop tank weight to increases in core inert weight for a fixed payload weight?

a) Fixed Gross Weight

The payload and core inert weights are presented in Figure 8 for various gross weights and core fixed weights (core fixed weight is a component of the core inert weight). It is quite evident from Figure 8 that for the small payload weights, should the inert weight increase, the payload would be reduced substantially if the gross weight is held constant. For the 10,000 pound payload reference point on Figure 8, a 16% increase in inert weight reduces the payload to zero. For the 50,000 lb payload, however, a 16% increase in inert weight reduces the payload to 34,500 pounds, a 31% reduction. This effect is summarized in Figure 9 for a range in potential core inert weight growth, and three fixed gross weights with the corresponding initial payload sizes. Figure 9 reflects the fact that, in absolute weights, there is simply a one-to-one exchange between core inert weight and payload weight and that payload is a much smaller fraction of core inert weight at the smaller sizes.

b) Fixed Payload

If, on the other hand, the drop tanks are allowed to increase to compensate for core inert weight growth, the payload capability can be held constant. This effect is illustrated in Figure 10. A 16% increase in the core inert weight could be compensated for with a 18% increase in drop-tank size for the 10,000 lb payload system and 14% increase in drop-tank size for the 50,000 lb payload system. The corresponding gross weight increases are 16% and 12.5% respectively.

Since the lift-off thrust to weight ratio would be reduced as the gross weight increases, the amount of drop-tank growth would be restricted by the capability of the engines. Therefore, in order to compensate for potential gross weight growth, the engine system would have to be oversized for the nominal (no growth) design. This larger engine system would impact the SOH nominal design with added engine weight and volume, but due to the increased thrust to weight ratio, at least the payload lifting capability would be the same or slightly increased at nominal weight.

Conclusions

A SOH system of fixed design, although sensitive to inert weight variations, can be made substantially less sensitive and the growth factor reduced if sized for larger payloads, since there is a large fixed weight in the core vehicle associated with subsystems and structure which is independent of payload. For small payloads, if the gross weight (and drop-tank weight) is held constant, inert weight growth can rapidly reduce the payload to zero. A system sized for large payloads is much less sensitive since the core inert weight does not grow proportionally.

If, on the other hand, the drop tanks are allowed to grow to compensate for inert weight growth, the required percentage increase in drop tank and gross weight to maintain a fixed payload can actually be less than the percent increase in the core inert weight for large payloads. The large payload system in this case is somewhat less sensitive than a small payload system as well. Oversized engines would have to be included in the nominal design to provide for gross weight growth.

D. E. Cassidy

J. J. Schoch

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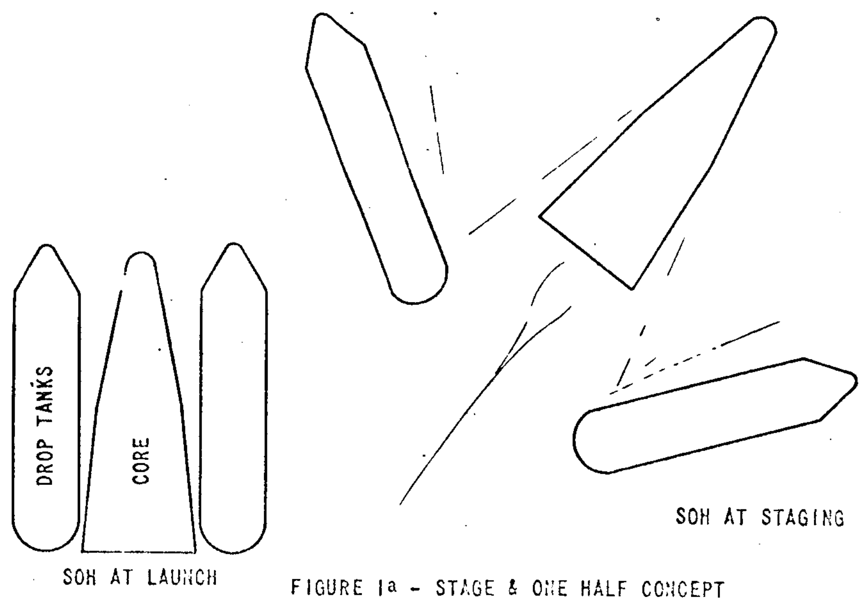
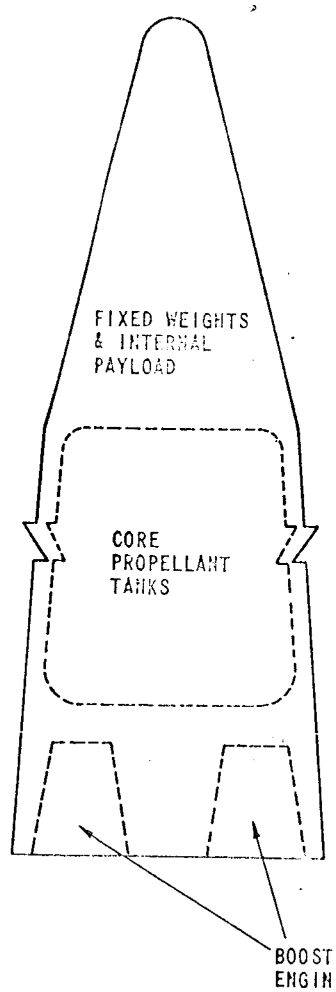


FIGURE 1a - STAGE & ONE HALF CONCEPT



ADDITIONAL WEIGHT FACTORS

- SHELL STRUCTURE
- REENTRY HEAT PROTECTION
- RECOVERY
- ORBITAL PROPULSION

FIGURE 1b - STAGE & ONE-HALF CORE INERT WEIGHTS SCHEMATIC

	WEIGHT RANGE (Pounds)		
STRUCTURE	10,000	→	15,000
ELECTRIC POWER	2,500	→	3,000
ENVIRONMENTAL CONTROL	1,400	→	1,800
CREW SYSTEMS	1,400	→	1,600
OTHER SUBSYSTEMS	3,000	→	3,000
TOTAL	18,300	→	24,400

FIGURE 2: APPROXIMATE FIXED WEIGHT

DEFINITIONS

WG , GROSS WEIGHT AT LAUNCH
T , THRUST AT LAUNCH
WE , TOTAL WEIGHT OF BOOST ENGINES
WIC , CORE VEHICLE TOTAL INERT WEIGHT = WIEO - WPL
WPC , CORE VEHICLE ASCENT PROPELLANT WEIGHT
WFIX, FIXED WEIGHT IN CORE
WIEO, WEIGHT IN EARTH ORBIT
WPL , PAYLOAD WEIGHT
WOM , PROPULSION FOR ORBIT MANEUVERING & DEORBIT
KE , STRUCTURAL FACTOR FOR ENGINES = .10
KPL , STRUCTURAL FACTOR FOR PAYLOAD

ASSUMPTIONS

(1) RESIDUAL PROPELLANT IN CORE IS 2% WPC
(2) CORE PROPELLANT TANKS AND ASSOCIATED STRUCTURE IS 10% WPC
(3) 1300 FPS ΔV FOR ORBIT MANEUVERS AND DEORBIT
(4) 14% OF THE CORE ENTRY WEIGHT REQUIRED FOR ENTRY HEAT PROTECTION SYSTEM
(5) 14% OF CORE ENTRY WEIGHT REQUIRED FOR LANDING SYSTEM
(6) (4) & (5) YIELD THAT 39% OF INERT WEIGHT FOR ENTRY AND LANDING
(7) T/WE = 90
(8) T/WG = 1.25

(i) $$WE = \left(\frac{WE}{T}\right) \cdot \left(\frac{T}{WG}\right) \cdot (1 + KE) \approx .015\ WG$$

(ii) $$WPL(1 + KPL) = WIEO - .12WPC - WFIX - WOM - WE$$
$$- .39\ (WFIX + .1WPC + KPL \cdot WPL + .1WOM + WE)$$

FOR 1300 FPS ΔV, WOM = .13WIEO

(iii) $$WPL(1 + 1.39KPL) = .865WIEO - .156WPC - 1.39WFIX - 1.39WE$$

FIGURE 3: WEIGHT SCALING RELATIONS

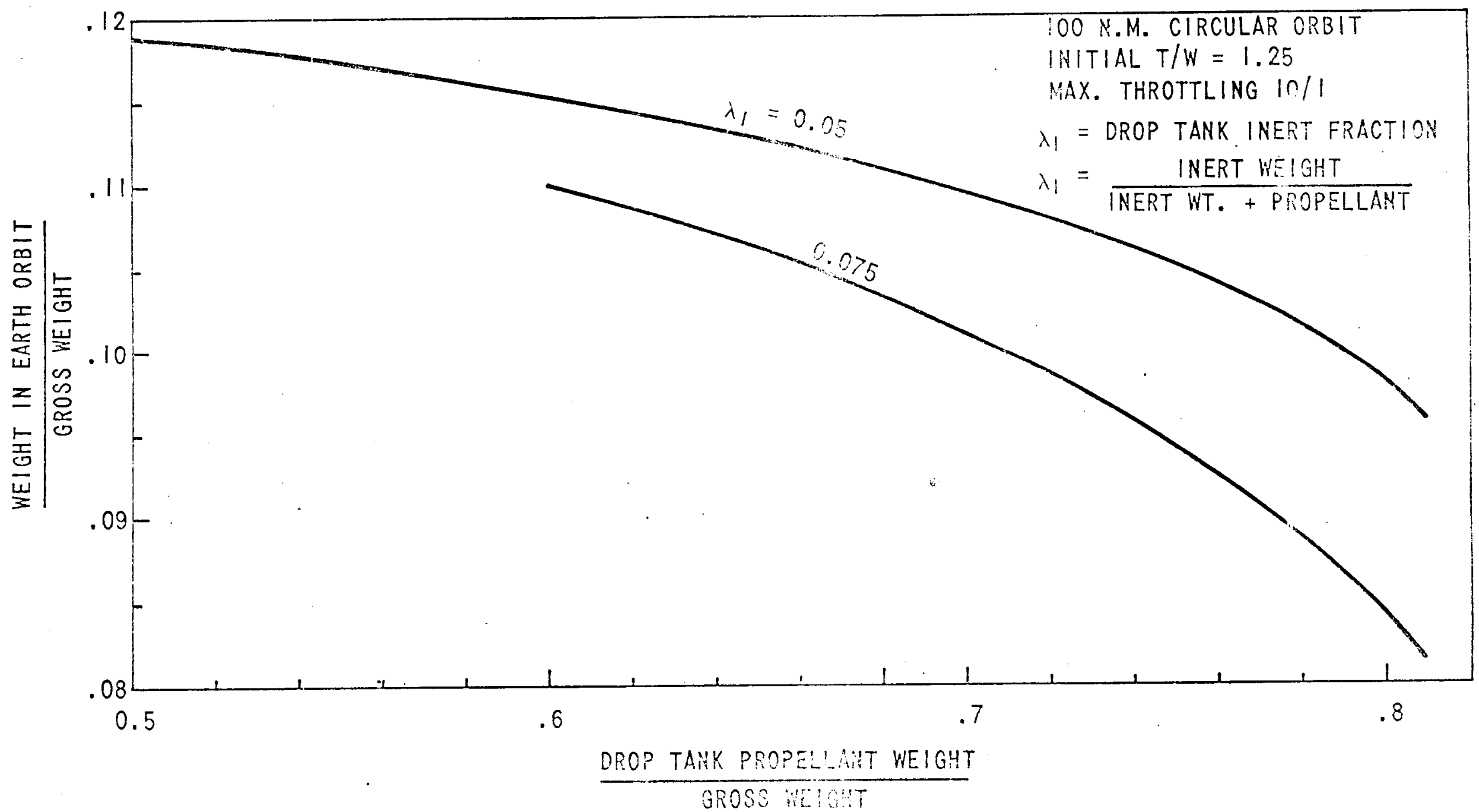


FIGURE 4 - WEIGHT IN EARTH ORBIT vs DROP TANK PROPELLANT WEIGHT

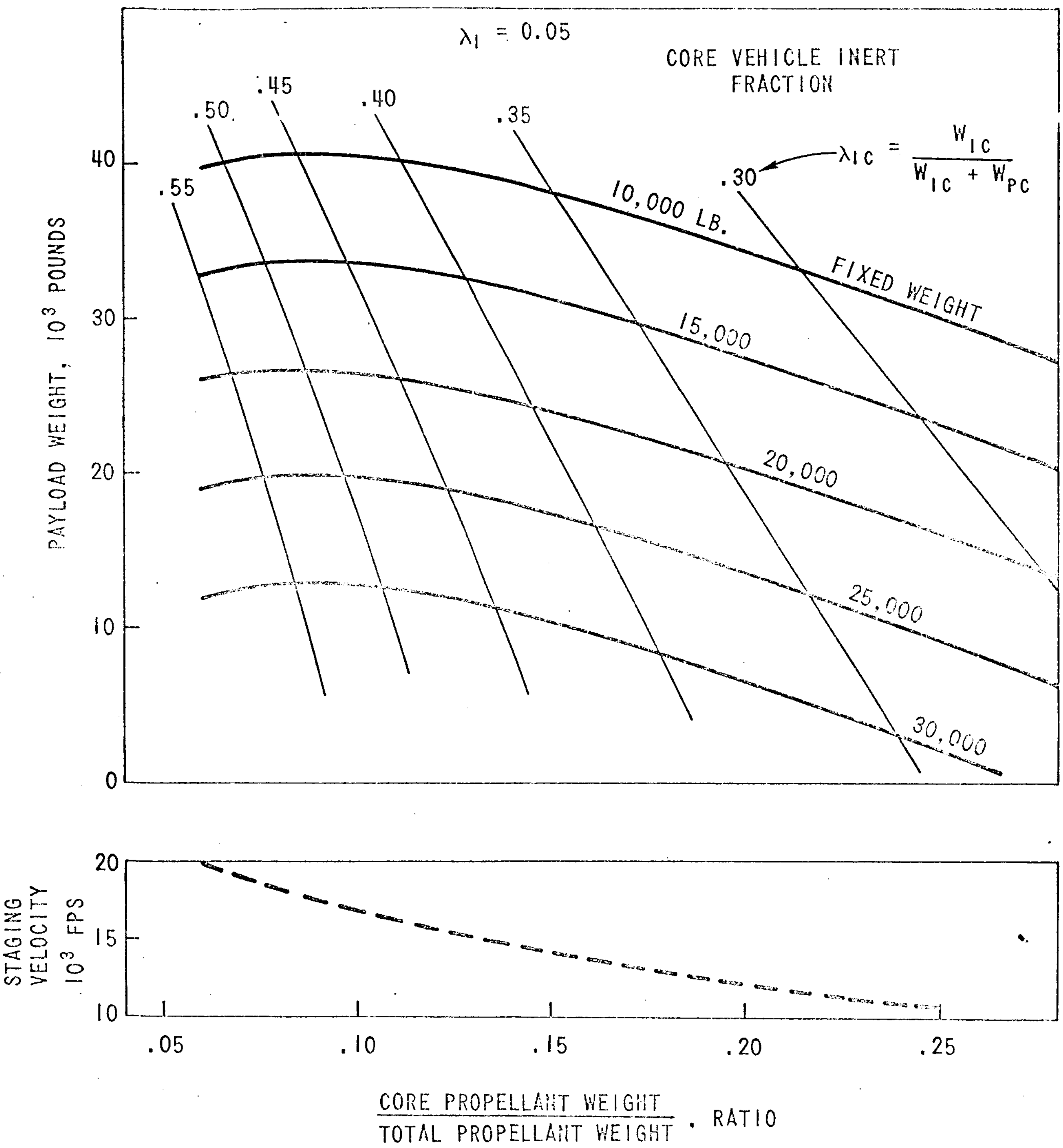


FIGURE 5 - PAYLOAD WEIGHT vs CORE PROPELLANT FRACTION
(MILLION POUND GROSS WEIGHT)

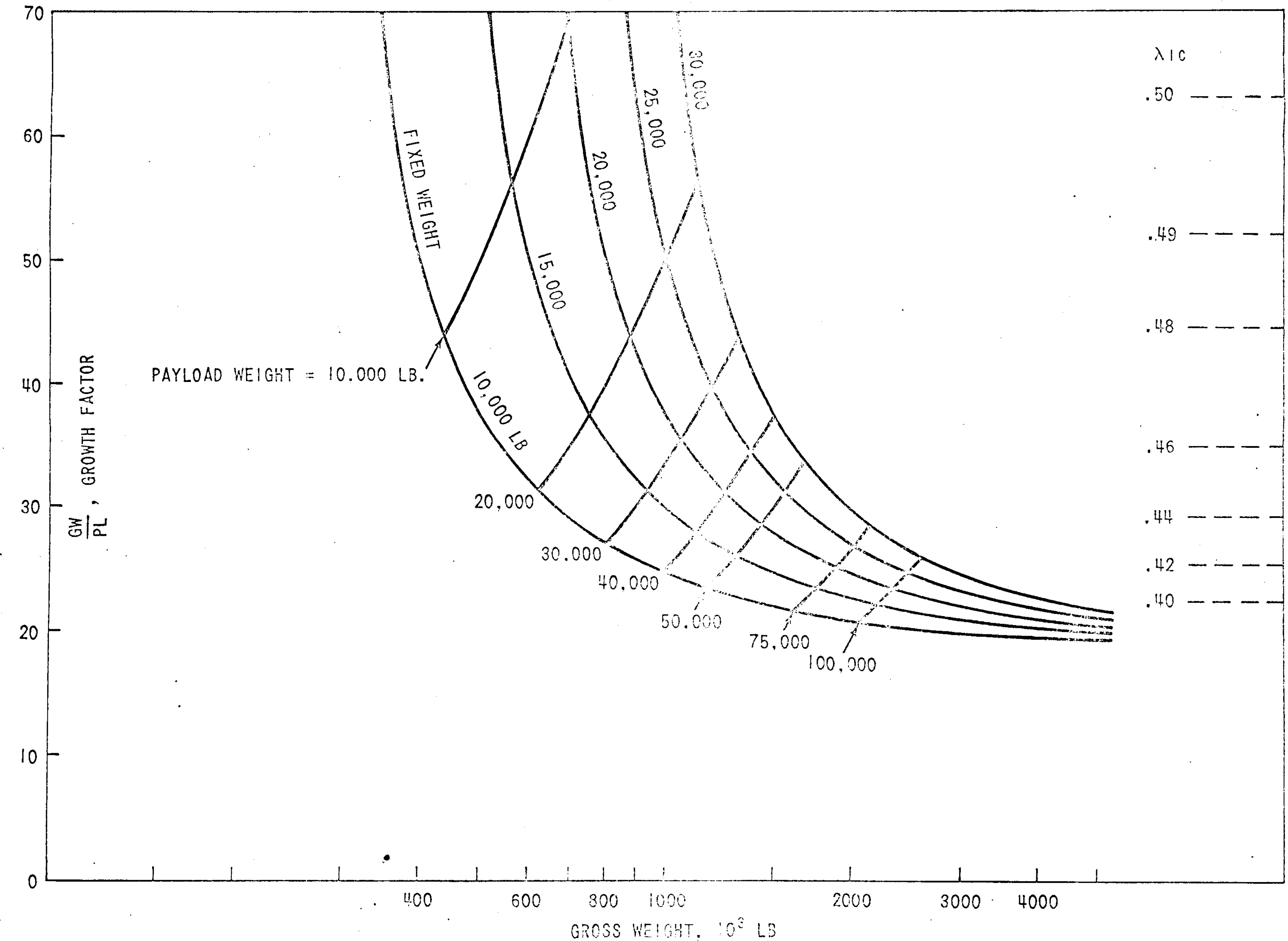


FIGURE 6 - GROWTH FACTOR vs GROSS WEIGHT

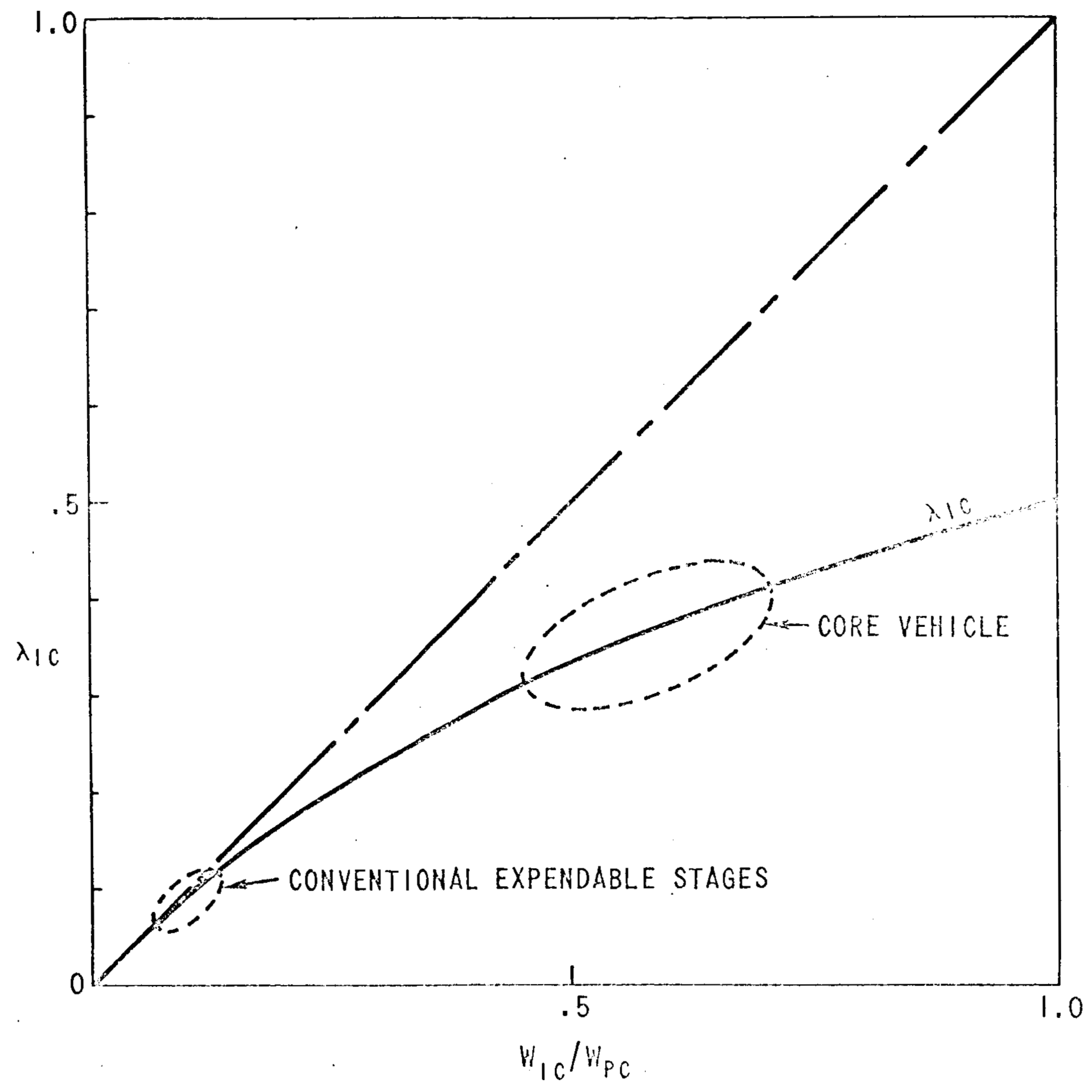


FIGURE 7 - CORE INERT WEIGHT FRACTION (λ_{IC}) VS. RATIO OF CORE INERT WEIGHT TO CORE PROPELLANT WEIGHT (W_{IC}/W_{PC})

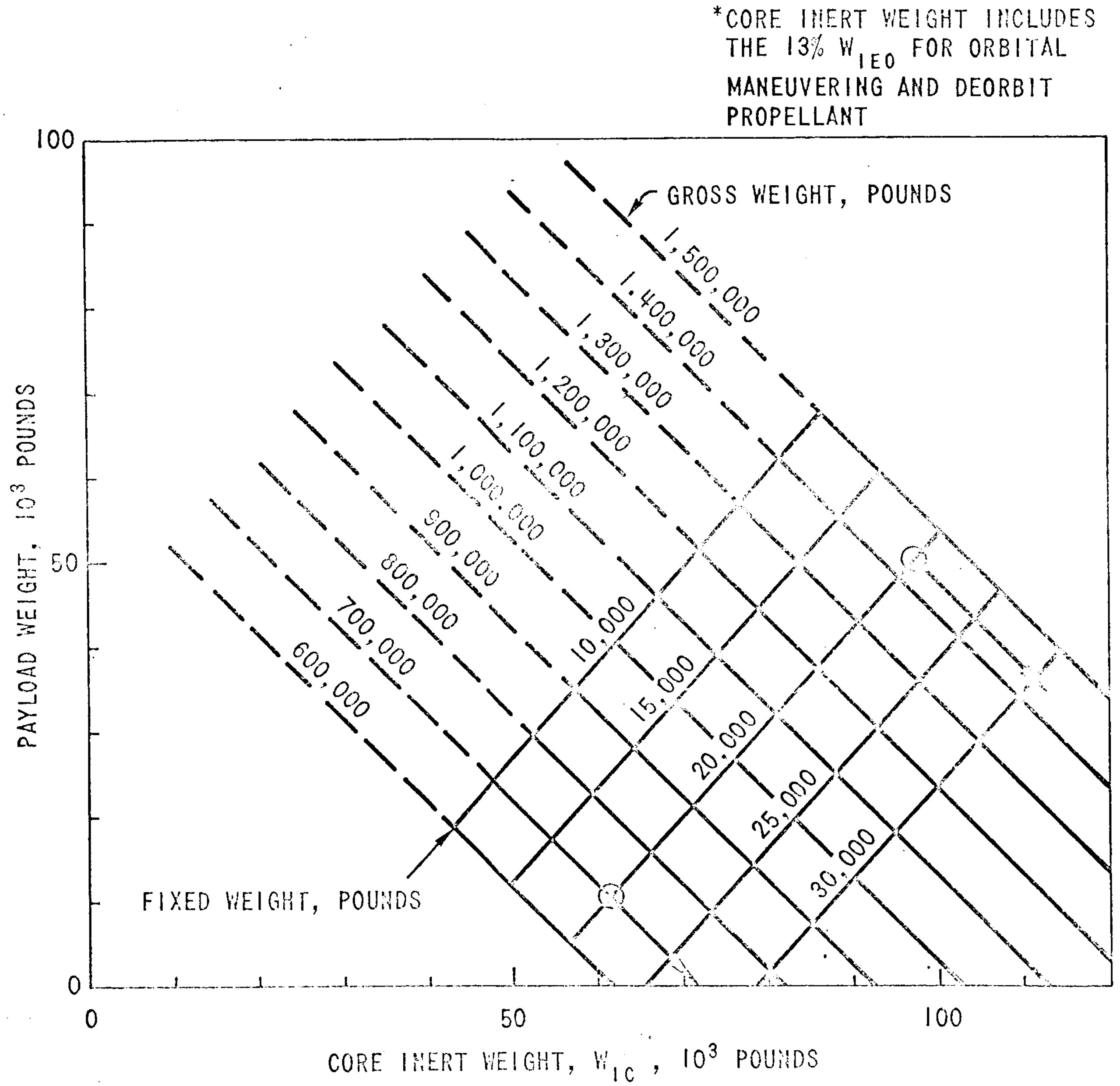


FIGURE 8 - PAYLOAD WEIGHT vs CORE INERT WEIGHT*

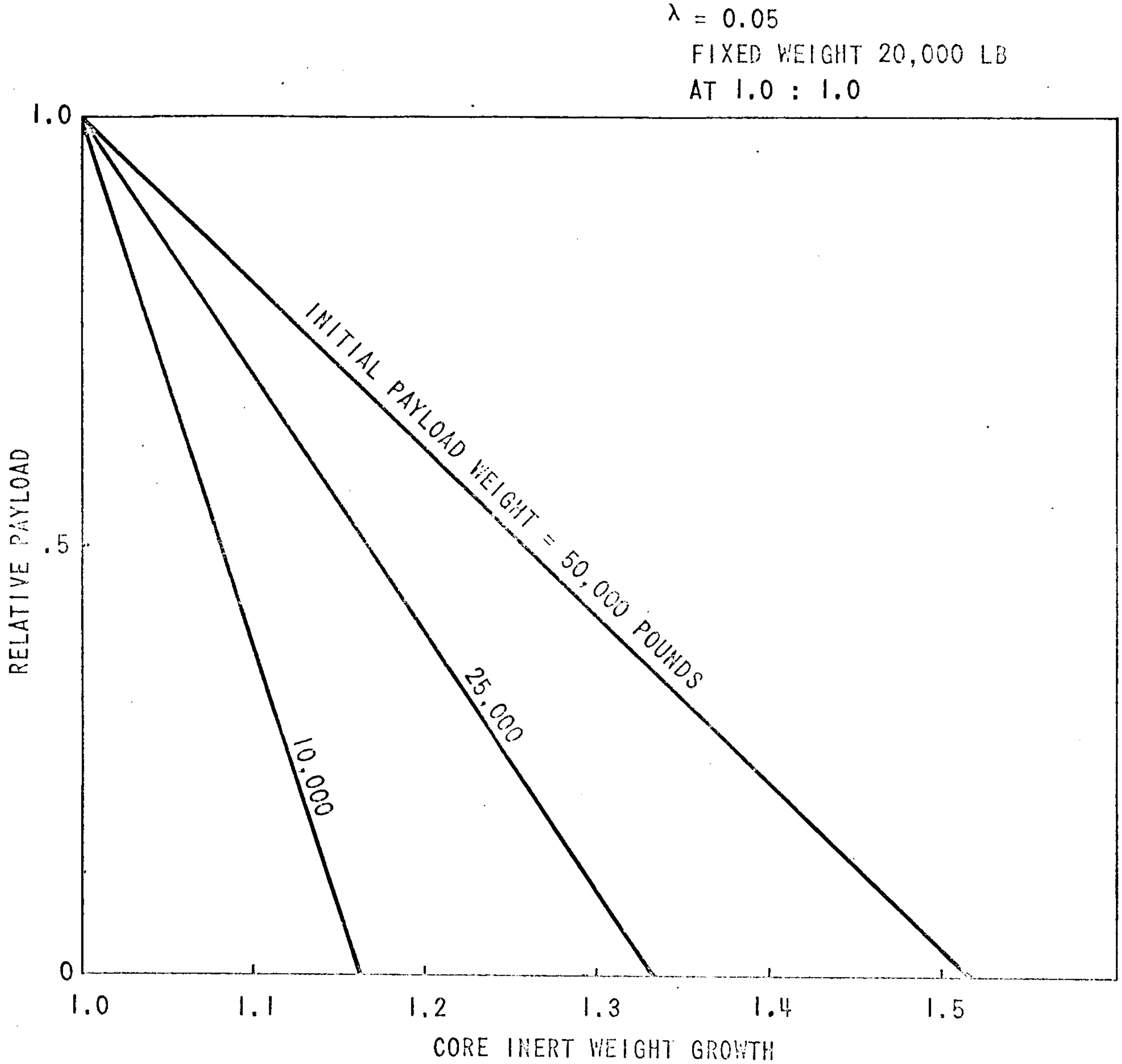


FIGURE 9 - PAYLOAD SENSITIVITY TO CORE INERT WEIGHT GROWTH FOR FIXED GROSS WEIGHT

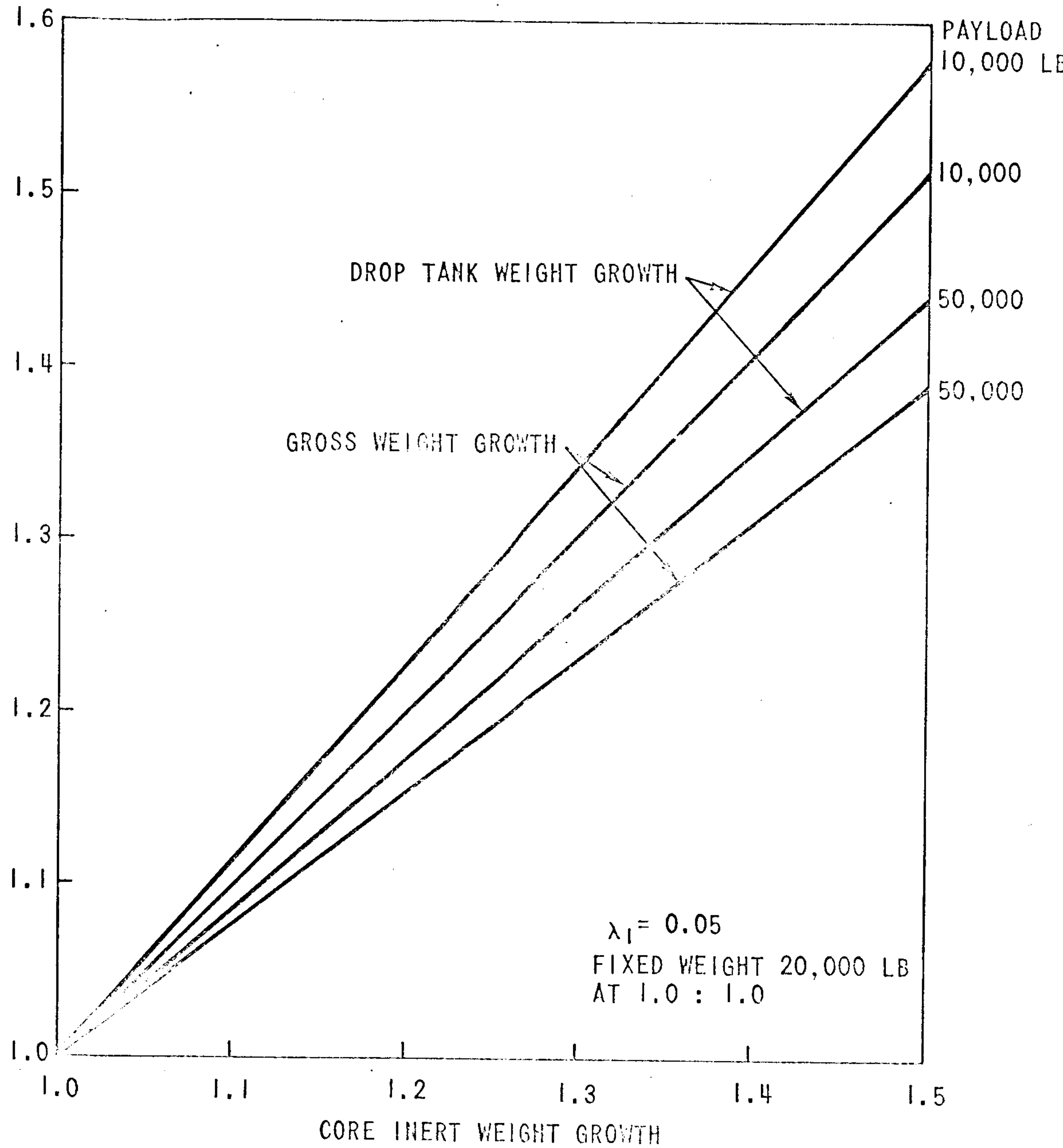


FIGURE 10 - GROSS WEIGHT AND DROP TANK WEIGHT SENSITIVITY TO CORE INERT WEIGHT INCREASE FOR CONSTANT PAYLOAD